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Insights into Nuclear Clusters in ^{28}Si via Resonant Radiative Capture Measurements

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Abstract. The heavy-ion radiative capture reaction ^{12}C(^{16}O,γ)^{28}Si has been studied at three energies on- (E_{Lab} = 20.0 and 21.2 MeV) and off- (E_{Lab} = 20.7 MeV) resonance at Triumf (Vancouver) using the state-of-the-art Dragon 0° spectrometer and its very efficient associated BGO γ array. Intermediate states around E_x = 11.5 MeV, carrying a large part of the resonant flux have been observed for the first time in this system. The nature of those doorway states is discussed in terms of recently calculated cluster bands in ^{28}Si. The results are compared to a recent similar investigation of the ^{12}C(^{12}C,γ)^{24}Mg reaction.

1. Introduction

Radiative capture is the complete fusion of the target nucleus and projectile, forming a compound nucleus (CN) which is subsequently cooled by γ emission only. This process reveals a powerful tool to determine the spectroscopic overlap between the entrance channel and the CN lower lying bound or quasi-bound states.

The radiative capture of light particles (α, p, n) has been extensively studied particularly for astrophysical purposes since, for example, it is part of the nucleosynthesis of medium mass nuclei in novae. It has been much less explored what heavy-ions are concerned since the Coulomb barriers are much higher and thus the competition with the fusion-evaporation channels very strong, making each experimental study a real challenge. A complete review of radiative capture reactions involving heavy-ions can be found in ref. [1].

Resonances are a well established feature of certain reactions between light heavy-ions. Their selective occurrence is well understood in terms of the phase space the system has access to: resonances are most likely observed when the number of open channels is small [2]. $^{12}C+^{12}C$ and $^{12}C+^{16}O$ are systems where resonant effects are the strongest, particularly in resonant radiative capture reactions. The link between a resonant state and a cluster configuration in the composite system has nevertheless not been experimentally established.

2. Resonances in the $^{12}C(^{16}O,\gamma)^{28}Si$ reaction

Strong and narrow resonances have been observed by Collins *et al.* in the $^{12}C(^{16}O,\gamma)^{28}Si$ capture reaction at energies close to the Coulomb barrier [3]. These resonances correspond to a long lifetime for the composite system and could thus be a perfect laboratory for the search for a link between a resonant state in the entrance channel and a ^{12}C-^{16}O nuclear molecular configuration in ^{28}Si. The experimental setup used by Collins *et al.* was based on a large NaI detector. The piling up of low energy γ-rays in this device from the fusion-evaporation dominant channels did not allow to measure γ-rays of energies < 12-15 MeV. For this reason, the authors could not measure the decay of the resonant states to eventual intermediate bound states of ^{28}Si at E_x around 11 MeV.

Following our successful study of the $^{12}C(^{12}C,\gamma)^{24}Mg$ resonant radiative capture reaction [4], we have decided to re-explore the $^{12}C(^{16}O,\gamma)^{28}Si$ reaction taking advantage of the state-of-the-art Dragon 0° spectrometer installed at the Triumf laboratory in Vancouver coupled to an extremely efficient BGO γ array (ε = 50% at 5 MeV) to search for the γ decay of the resonances via intermediate *doorway* states of ^{28}Si.

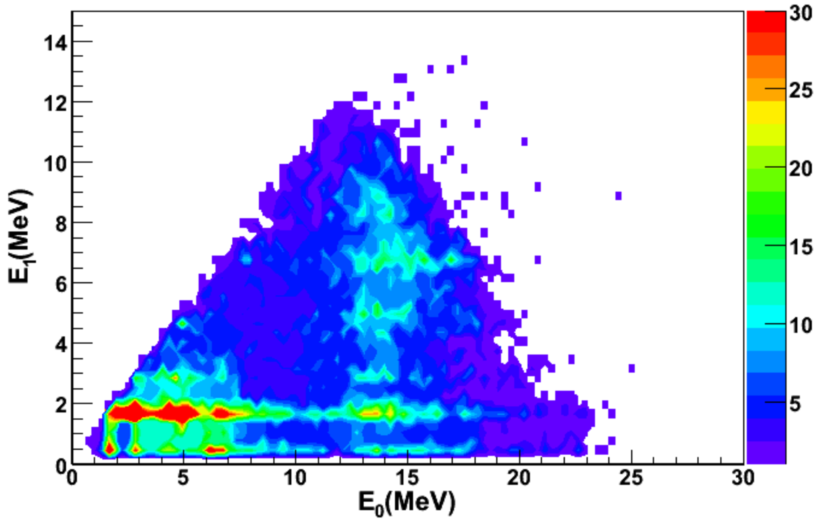

Fig. 1: E_0 vs E_1 γ spectrum measured in the BGO array at E_{Lab} = 20.0 MeV in coincidence with the ^{28}Si recoils.

3. The Dragon experiment

The ^{16}O beam has been delivered by the ISAC1 accelerator using the OLIS source for stable beams at three energies, on- (E_{Lab} = 20.0 and 21.2 MeV) and off- (E_{Lab} = 20.7 MeV) resonance on highly enriched ^{12}C targets. We have measured the complete γ decay of the ^{28}Si CN at E_x = 25.3, 25,6 and 25.8

MeV in 30 BGO counters around the target, the ^{28}Si recoils being detected in a 250 μm Double Sided Silicon Strip Detector (DSSSD) at the focal plane of the Dragon spectrometer [5]. Dragon has been designed to study light particle radiative capture reactions of astrophysical interest in inverse kinematics using a windowless gas target. It is therefore extremely performing in rejecting the incoming beam (the rejection factor is 10^{12} for our experiment); its acceptance is none the less restricted to a cone of half angle 25 mrad for heavy ion capture reactions.

4. Results and discussion

Fig. 1 shows a 2D γ spectrum measured at the first resonance energy in coincidence with the ^{28}Si recoils. Gamma-ray events are energy ordered in such a way that E_0 is the highest energy γ-ray in the cascade, E_1, the second highest energy γ-ray, and so on. We clearly see transitions between the low-lying states of ^{28}Si: 1.79 MeV ($2^+ \rightarrow 0^+$), 2.84 MeV ($4^+ \rightarrow 2^+$); the regions around 4.5 MeV and 6.5 MeV, probably correspond to the decays of the ^{28}Si 3^+ (6.28 MeV), 0^+ (6.69 MeV) and 3^- (6.88 MeV).

A striking feature of this spectrum is the large number of events around 13.5 MeV. This would correspond to a relatively strong feeding of intermediate states in ^{28}Si around 11.5 MeV.

Monte Carlo GEANT3 simulations have been performed to compute the response of the BGO array in coincidence with the recoiling nuclei in the DSSSD. All elements of the Dragon separator have been included in the simulations allowing the recoils to be fully tracked down to the DSSSD end detector at the focal plane. Those simulations are extremely important because of the limited acceptance of Dragon, for example, recoils emitting high-energy γ-rays are likely to be kicked out of the separator. This effect has been fully taken into account in the calculations.

Fig. 2 shows the spectrum of the highest energy γ-ray detected in the cascade at the first resonance energy, compared to simulations (blue) corresponding to a scenario suggested previously by Collins et al., i.e. a strong decay through the 0^+, 2^+ and 4^+ members of the ^{28}Si prolate band. This scenario is clearly different from what we observe in the data where we see that a large amount of the resonant flux feeds states around 11.5 MeV, corresponding to the region around 13.5 MeV in the γ spectrum.

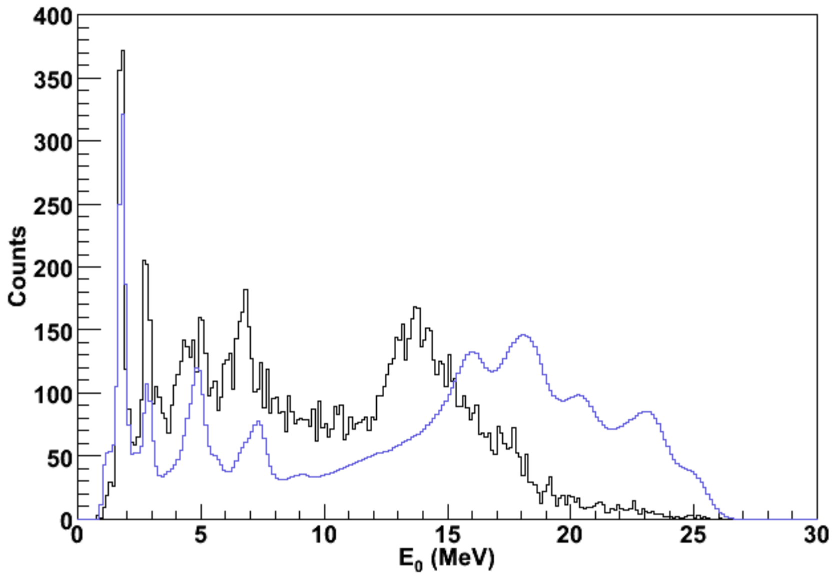

Fig. 2: Spectrum of the highest energy γ-ray (dark) detected in the cascade at the first resonance energy, in coincidence with ^{28}Si recoils at the focal plane, compared to GEANT3 simulations (blue). See text for more details.

Similar doorway states have been observed in our recent study of the ^{12}C(^{12}C,γ)^{24}Mg resonant radiative capture reaction [4]. There we have explored four resonances in this system using the same experimental setup at Triumf. The relative strength of all decay pathways has been measured. The data has been compared to Monte-Carlo simulations. Fig. 3 shows γ spectra measured in the BGO array in coincidence with ^{24}Mg residues in the DSSSD, at the lowest resonance energy (E_{CM} = 6.0 MeV). The data is compared with simulations assuming a spin 0^+ (a.) and 2^+ (b.) for the 6.0 MeV resonance. Decay through all states known in the literature for ^{24}Mg and the corresponding branching ratios have been included. This study has allowed us to propose some spin assignments for the resonances, but states involved in the decay have not yet been clearly identified due to the low resolution of the BGO detectors.

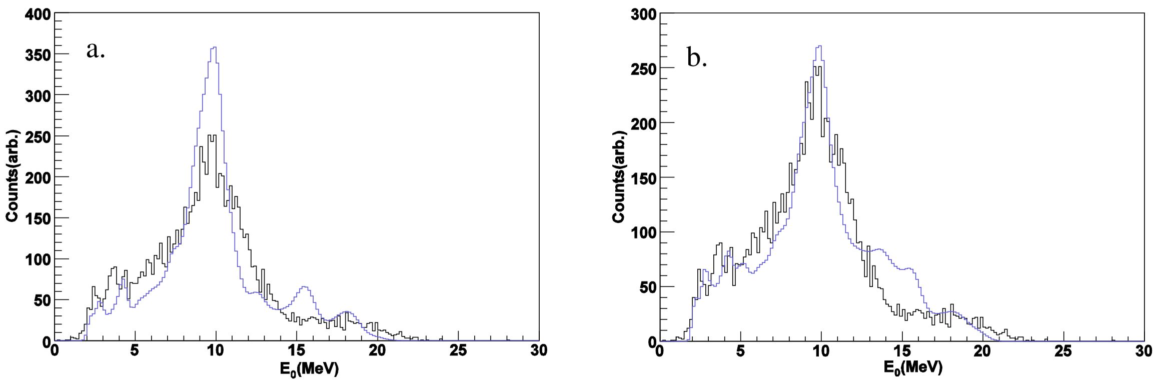

Fig. 3: ^{12}C(^{12}C,γ)^{24}Mg reaction: γ spectra measured in the BGO array at the E_{CM} = 6.0 MeV resonance energy. The data (dark) is compared with Monte-Carlo simulations (blue) assuming a 0^+ (a.) and a 2^+ (b.) resonance.

For both experiments, different scenarii can be suggested for the decay of the resonant states.

Extensive experimental studies have been carried out concerning ^{12}C+^{12}C and ^{12}C+^{16}O breakup states in ^{24}Mg and ^{28}Si by the Charissa collaboration [6,7]. For both systems, cluster breakup states have been observed up to about E_x = 45-50 MeV in the composite nucleus. The moment of inertia associated to the breakup bands corresponds to a very large ‘cluster-type’ deformation. For experimental reasons, low energy – and low spin – members of these bands could not be observed. The radiative capture mechanism allows to explore this low energy region since it concerns the composite system, at the Coulomb barrier, at an excitation energy corresponding to the head of those bands.

Cluster bands have been predicted in ^{24}Mg and in ^{28}Si. Descouvemont and Baye have described cluster configurations in ^{24}Mg(^{12}C-^{12}C) in the generator coordinate method framework [8]. They have predicted a first excited band starting around E_x = 12 MeV and a second excited unbound cluster band starting around E_x = 18 MeV. What ^{28}Si is concerned, recent calculations have been carried out by Ohkubo and Yamashita [9]. Parity doublet cluster bands have been predicted using a deep potential determined from ^{12}C+^{16}O rainbow scattering data measured in our group by Nicoli *et al*. [10]. Negative and positive parity cluster bands are found, as shown on Fig. 4.

For both cases, our measured γ transitions could be links between the low lying members of the cluster excited bands.

Another possible scenario for the decay of the resonances has arisen from our numerical simulations for the $^{12}C+^{12}C$ system. Allowed isovector M1 $\Delta T = 1$ transitions could play an important role in carrying the resonant flux in the self-conjugate ^{24}Mg nucleus. The analysis of the $^{12}C(^{16}O,\gamma)^{28}Si$ reaction and the corresponding simulations are still under progress to see if such a scenario would also be possible there.

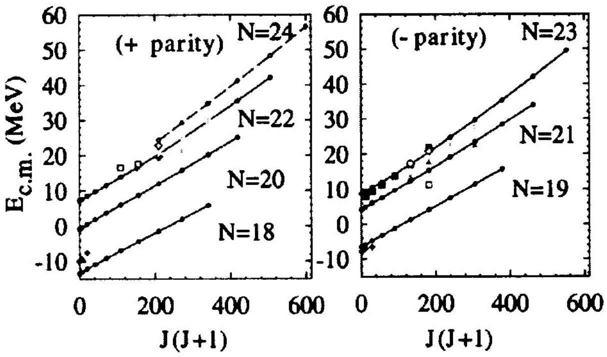

Fig. 4: Calculated $^{12}C+^{16}O$ cluster bands from [9]. N is related to the number of nodes in the relative cluster wave function.

5. Conclusion

We have re-opened the study of the resonant radiative capture reactions $^{12}C(^{12}C,\gamma)^{24}Mg$ and $^{12}C(^{16}O,\gamma)$ ^{28}Si using a much higher performing experimental setup than Sandorfi *et al.* pioneering studies from the 80ies.

Our most important result is the observation of γ transitions feeding doorway states of ^{24}Mg and ^{28}Si around 10 and 11.5 MeV respectively.

The nature of these states is still to be established:

- T = 1 states which could play an important role in ^{24}Mg and ^{28}Si because of the electromagnetic selection rules in self-conjugate nuclei,
- cluster states which nature would overlap the highly deformed entrance channel.

The observations of the present work would thus be the first evidence of γ transitions between resonant states in the entrance-channel and molecular states of the CN.

Concerning the $^{12}C+^{12}C$ system, a recent experiment has been performed at Argonne National Laboratory using the Atlas facility and the FMA large acceptance spectrometer for recoil detection associated to the gammasphere array for γ detection to identify the energies of the doorways states in ^{24}Mg.

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